SIMULATION OF THE HYDROLOGIC EFFECTS OF AFFORESTATION IN THE TACUAREMBÓ RIVER BASIN, URUGUAY

N. O. von Stackelberg, G. M. Chescheir, R. W. Skaggs, D. M. Amatya

ABSTRACT. *The Soil and Water Assessment Tool (SWAT) was used to simulate the hydrology of two small paired catchments in northern Uruguay. The control and treatment catchments (69 and 108 ha, respectively) were monitored for a three-year pretreatment period during which the land use was grassland with livestock grazing. Subsequently, the treatment catchment was planted (57% afforested) with loblolly pine (*Pinus taeda*). The objectives of the modeling study were to simulate the hydrologic response of the two catchments during the pretreatment period and predict the hydrologic effects of converting the native pasture to pine plantation. SWAT models of the two catchments were calibrated and validated using data measured during the pretreatment period. The model predicted outflows from the catchments reasonably well as compared to observed outflows during the years with above average rainfall (5% to −13% error). Model efficiency (E) for daily outflow volumes was greater than 0.71, indicating a good fit between simulated and observed results. A 33-year continuous simulation was performed on three land uses: grassland with livestock grazing, grassland without grazing, and pine treatment. The conversion of the catchments from the baseline pasture condition with grazing resulted in a predicted reduction in average annual water yield from the catchments of 15% for native grassland without grazing, and 23% for pine trees. A maximum predicted hydrologic effect was estimated by maximizing the model parameter that increases the ability of pine trees to withdraw water from the ground. For this condition, the model predicted a 30% reduction in mean annual water yield from the afforested catchment.*

Keywords. *Afforestation, Hydrologic modeling, Hydrology, Loblolly pine, SWAT, Uruguay.*

Uruguay is a small country in South America that has 85% of its land mass (176,220 km^2) in agriculture, the highest percentage in the world. The predominant physiography of northern Uruguay is gently rolling hills with natural grassland that is typically free of woody plants (trees and shrubs). The grasslands in Uruguay have historically been used for livestock grazing, as they are productive rangelands for forage. In 1989, the Uruguayan government instituted financial incentives for the establishment of tree plantations in an effort to diversify the rural economy. In response, multinational timber corporations have purchased land and planted trees (primarily eucalyptus, loblolly pine, and slash pine) over significant portions of the landscape. Subsequently, local stakeholders have expressed concerns regarding the environmental impact on water resources of converting land from pasture to tree plantations. Of particular concern are the effects of the tree plantations on water yield and downstream water supply, as well as the impact on baseflows in the receiving streams and rivers.

Previous studies on afforestation conducted in Australia, New Zealand, South Africa, and Great Britain employed a paired catchment approach in which the control catchment remained grass and the treatment catchment was planted with trees. Previous reviews of the results of these studies have shown that the establishment of tree plantations on historical grasslands reduces rainwater yield from the landscape, thereby decreasing water flow to tributary streams and rivers (Hibbert, 1967; Bosch and Hewlett, 1982; Sahin and Hall, 1996; Best et al., 2003). The reduction in water yield has been found to be primarily due to the greater evapotranspiration from trees as compared to grass (Holmes and Sinclair, 1986; Zhang et al., 1999, 2001). One of the most extensive experimental data sets on afforestation, both in number of paired catchments and length of observations, is from South Africa (Scott et al., 2000). The catchments in South Africa with mean annual rainfall and potential evapotranspiration most similar to that of Uruguay are located at the Cathedral Peak Forest Influences Research Station, which has one control catchment of grassland and two treatment catchments of *Pinus patula* (75% and 86% afforested). The mean annual total flow reduction 16 to 20 years after planting was 58% and 45%, respectively, while the mean annual low flow reduction was 63% and 46%, respectively. Based on a comparison of previous studies (von Stackelberg, 2005), it was concluded that the effect on water yield due to afforestation is strongly dependent on the climate characteristics (rainfall and potential evapotranspiration) and catchment characteristics (soil and drainage properties) of the research site. No previous studies of afforestation have been conducted in Uruguay.

Submitted for review in December 2005 as manuscript number SW 6265; approved for publication by the Soil & Water Division of ASABE in January 2007.

The authors are **Nicholas O. von Stackelberg,** Consulting Engineer, Stantec Consulting, Salt Lake City, Utah; **George M. Chescheir, ASABE Member Engineer,** Research Assistant Professor, and **Richard Wayne Skaggs, ASABE Fellow Engineer,** William Neal Reynolds and Distinguished University Professor, Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina, and **Devendra M. Amatya, ASABE Member Engineer,** Research Hydrologist, USDA Forest Service, Charleston, South Carolina. **Corresponding author:** Nicholas O. von Stackelberg, Stantec Consulting, 3995 South 700 East, Suite 300, Salt Lake City, UT 84107; phone: 801-261-0090; fax: 801-266-1671; e-mail: nicholas.vonstackelberg@ stantec.com.

  ISSN 0001–2351

Methods

SWAT models were developed to simulate the hydrology of the two monitored catchments in Uruguay. The models were calibrated using weather and outflow data measured on the sites from July 2000 to June 2002. The calibrated models were validated using data measured from July 2002 to June 2004. During the calibration and validation study, two scenarios were used to account for higher total outflow and baseflow observed from one of the catchments during the pretreatment period. These scenarios, the reduced evapotranspiration scenario and the added groundwater scenario, will be explained in more detail later in this section.

The calibrated and validated model of the treatment catchment was then used to predict the hydrologic impact of converting the existing grazed grassland to natural grassland (not grazed) and to mature pine plantation. The hydrology of the catchment with each of the three different land uses was simulated using a 33-year (1971 through 2003) historical weather data set for the region. The impacts of each land use conversion were evaluated by comparing average annual outflows and the distribution of daily outflows. Since some uncertainty existed in the depth of tree root penetration and the availability of shallow groundwater to the tree roots, the model parameter affecting groundwater availability (GW_REVAP) was adjusted to evaluate its effect on the catchment hydrology and to present a possible range of water yield values.

Table 1. Summary of catchment characteristics.

Characteristic	Catchment D1	Catchment D2
Area (ha)	69.0	107.7
Elevation (m)	130 - 204	136 - 192
Pretreatment land use	Grassland grazed (97%)	Grassland grazed (97%)
Treatment land use	Grassland grazed (97%)	*Pinus taeda* (57%)
Mean annual rainfall (mm)	1,487	1,487
Mean annual potential ET (mm)	1,215	1,215

Catchment Characterization

The SWAT model has intensive input data requirements, including topography, hydrography, soils, land cover, and weather. The input data for the catchments was compiled and analyzed in GIS.

The research site is located within the Tacuarembó River basin in northern Uruguay (fig. 1). Two adjacent catchments (D1 and D2) with similar drainage area, topography, slope, aspect, soils, and vegetation were selected for instrumentation on the La Corona estancia of the El Cerro tract owned and managed by Colonvade, S.A. A summary of catchment characteristics is presented in table 1. Catchment D1 has a drainage area of 69.0 ha, and catchment D2 has an area of 107.7 ha. The aspect of catchment D1 is primarily to the east, while catchment D2 faces south and east.

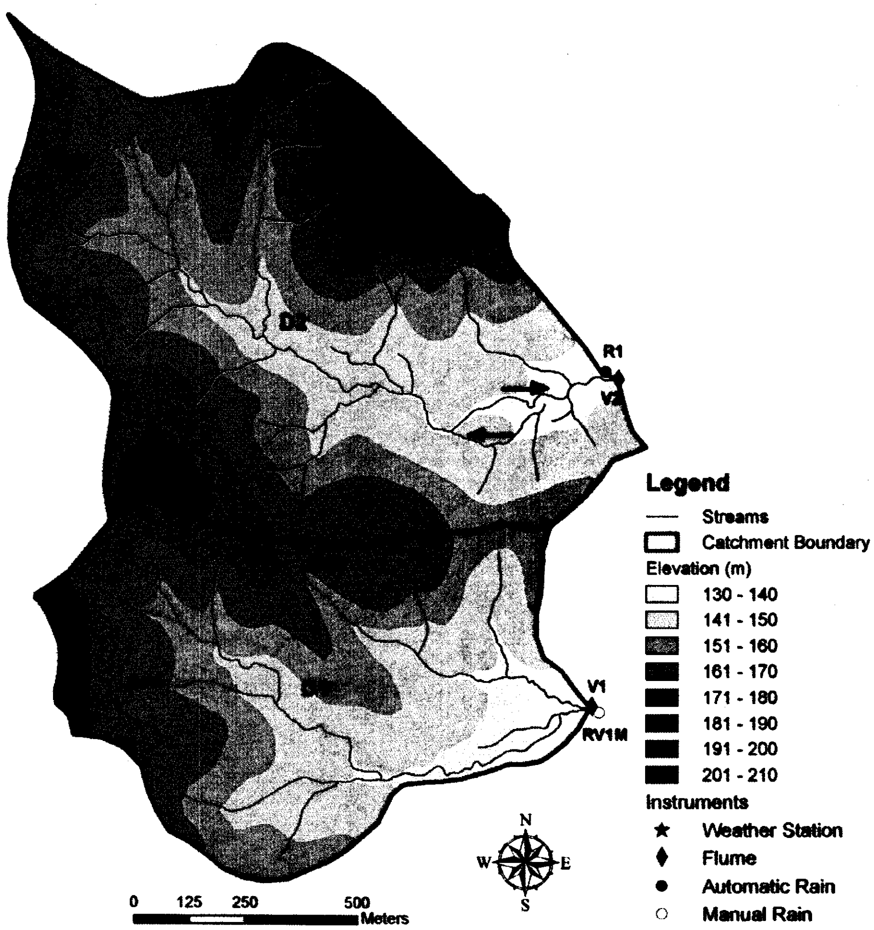

Figure 2. Topography, hydrography, and instrumentation on the research catchments.

red through erosive processes over many centuries. The alignment of the stream network was digitized in GIS based on aerial photographs of the site (fig. 2). The average slope of the stream channel ranges between 4% and 10% in the tributaries in the upper elevations of the catchments and between 1% and 1.5% in the main channel in the lower portion. Stream cross-sections were surveyed at selected locations in order to characterize the geometry of the channels for use in the model.

The soils on the catchments in the lower and middle elevations are dominated by sandy loam and sandy clay loam material of varying depth over sandstone. The higher elevations are outcroppings of basalt and sandstone overlain by a shallow topsoil layer. The soils on the site were investigated, classified, and mapped by Molfino (2000). Additional physical and chemical characterization of a subset of the soil map units was conducted by Préchac et al. (2004). The soil map developed by Molfino (2000) was digitized and entered into the GIS database (fig. 3). Soil map unit properties and areas for each catchment are summarized in table 2. Catchment D2 has a higher proportion of the very shallow upper elevation soils (A and E) than D1.

The general vegetation biome of most of Uruguay, including the research site, is grassland (Dasmann, 1984). A vegetation survey was conducted that identified the classification and frequency of the predominant grass species present in each type of soil in the study catchments (Marchesi, 2003). The two catchments were managed as grassland with livestock grazing during a three-year pretreatment period (July 2000 through June 2003). Grazing density for the period was estimated by Colonvade, S.A., field personnel to be 0.9 cattle units per hectare. One cattle unit is defined as the foraging needs of one cow of 380 kg weight with calf. The treatment catchment (D2) was planted with loblolly pine seedlings (*Pinus taeda*) in July 2003, while the control catchment (D1) remained grassland with livestock grazing. Riparian corridors, equipment access lanes, and cliff faces were not planted, resulting in 57% afforestation of catchment D2. The trees were planted in furrows (approx. 10 cm deep and 70 cm wide) and spaced approximately 2.5 m apart. Planting density was 1,000 trees per ha, per the standard planting practices of Colonvade, S.A. The area between furrows was left with grass vegetation, and the furrows were aligned perpendicular to the hillslopes. Cattle and sheep were not allowed to graze on the treatment catchment for approximately three years after tree planting. Livestock will then be allowed to graze on the treatment catchment at reduced grazing densities. The pine trees will be pruned and thinned periodically, per the standard management practices of Colonvade, S.A.

The general climate for most of Uruguay, including the research site, is mid-latitude humid subtropical grassland (Cfa) according to the Köppen climate classification system. The humid subtropical climate has hot, humid summers with frequent thunderstorms and mild winters with precipitation resulting from mid-latitude cyclones. Average annual rainfall measured at a weather station operated and maintained by Instituto Nacional de Investigación Agropecuaria (INIA), an Uruguayan governmental agency, in the town of Tacuarembó (35 km south of the research site) was 1,487 mm for the 26-year period from 1979 through 2004. Rainfall varied from as low as 841 mm in 2004 to as high as 2,797 mm in 2002. The rainfall is fairly uniformly distributed throughout the year, with slightly less rainfall in the months of June, July, and August than in other months. The estimated average annual potential evapotranspiration (PET) from the INIA station was 1,215 mm.

Data Collection

The instrumentation on the project site included a weather station, an automatic rain gauge, four manual rain gauges, and flow stage gauges at two outlet flumes (fig. 2). The weather station measured rainfall, air temperature, relative humidity, wind speed, wind direction, solar radiation, and net radiation on a 30 s interval and averaged or summed the data for recording on a 15 min basis. The additional automatic and manual rain gauges provided backup to the weather station and measurement of rainfall spatial variability across the catchments. Flow rates at the outlet of the two experimental catchments were measured using 1.37 m high HL flumes (Amatya et al., 2001). A calibrated rating curve provided by Bos (1989) was used to estimate flow rates through the flume outlet from measured flow stages. If stage elevations exceeded the 1.37 m maximum height of the stainless steel HL flume, flow rates were calculated assuming a broad crested weir located at the top of the HL flume. The catchments were continuously monitored from the beginning of July 2000 through June 2004, with continued monitoring planned through the growth and harvesting of the pine trees. More detailed information regarding the data collection at the research site can be found in Chescheir et al. (2004).

Model Setup and Parameterization

A hydrologic model of both catchments was created, calibrated, and validated using the SWAT model. SWAT is a semi-physically based, lumped parameter, deterministic, continuous model that relies on detailed soil and plant cover characteristics. GIS data layers were compiled for the AVSWAT2000 (Di Luzio et al., 2002) GIS interface for the SWAT model, including topography, hydrography, soils, and land use, as previously discussed.

The curve number method of estimating surface runoff and infiltration was used in SWAT on a daily time step. The curve number is an empirical index used to relate rainfall to runoff for various types of soil and land cover. Curve numbers for the soils on the watersheds were determined by model calibration. The calibrated curve number values generally correlated with poor to fair hydrologic condition for each hydrologic soil group and land cover, as determined by the Soil Conservation Service (SCS) (Neitsch et al., 2002b). Somewhat higher curve numbers were selected for mixed forest vegetation in the cliff land use to account for the predominant steep and rocky cliffs in these areas and sparse cover of the vegetation.

Initial soil parameters for the model were assigned based on laboratory analysis of on-site soil samples (Molfino, 2000; Préchac et al., 2004). Parameters for soil map units that were not sampled were estimated using the Rosetta computer program (Schaap, 1999). The Rosetta program estimates soil hydraulic properties such as available water capacity and saturated hydraulic conductivity from soil texture data.

The SWAT model tracks plant growth in order to simulate the hydrology of the landscape. The model requires the designation of land use areas that have similar vegetative cover and management. Land use/land cover GIS coverages were developed for the pretreatment and treatment condition

Table 3. Calibration and validation simulation periods and weather data sources.

Simulation		Period	Weather Data Source
Calibration model warm-up		1 Jan. 1999 - 30 June 2000	INIA Tacuarembó station
Calibration		1 July 2000 - 30 June 2002	Research site station
Validation model warm-up		1 Jan. 1999 - 30 June 2000	INIA Tacuarembó station
		1 July 2000 - 30 June 2002	Research site station
Validation	Control (catchment D1)	1 July 2002 - 30 June 2004	Research site station
	Treatment (catchment D2)	1 July 2002 - 30 June 2003	Research site station

coefficient (GW_REVAP) is the dimensionless fraction of water that moves upward and is assigned by soil type. A value of 0.02 was assigned to the A and B upper elevation soils and 0.20 to the remaining middle and lower elevation soil types, representing the minimum and maximum values, respectively, recommended by the model. The minimum value was selected for the upper elevation soils based on the rationale that the plant roots would have less access to the groundwater due to lesser depth of soil in these areas.

Model Calibration and Validation

The observed data record was divided into two periods for model calibration and validation (table 3). The model calibration period for both catchments was two years, with a 1.5-year model warm-up period. The model validation period was two years for the control catchment, and one year for the treatment catchment due to the tree planting that occurred in July 2003, which modified site conditions. Daily precipitation, temperature, relative humidity, total solar radiation, and wind speed data collected from the meteorological station on the research site were used for the model calibration and validation period. The daily potential evapotranspiration was estimated for a grass reference using the Penman-Monteith method (Allen et al., 1998; Chescheir et al., 2004). Both years in the calibration period were wetter than normal. The validation period had an extremely wet year followed by a dry year.

During the model calibration, model parameters were adjusted so that the outflows from the simulation most closely matched the observed outflows. The parameters that were adjusted during the calibration included curve number, hydraulic saturated conductivity, available water capacity, groundwater delay, baseflow recession, groundwater revap, and deep fraction (defined as the fraction of groundwater that percolates to the deep aquifer and is considered lost to the system). Once it was determined that the calibration was complete, the model was validated. The model validation consisted of assessing the performance of the model by comparing additional predicted versus measured outflows outside of the calibration period. Model parameters were not adjusted for the validation.

Evaluation Criteria

To evaluate the accuracy of the model calibration and validation, a comparison was made between simulated and observed water yield, flow hydrographs, and flow frequency curves. Two statistical measures were conducted to evaluate the "goodness of fit" between the simulated and observed daily flow data: linear regression analysis, and the coefficient of efficiency. Linear regression analysis uses the least squares error method to determine the best-fit line between simulated and observed data. The ideal regression line for the calibration would have a slope of 1.0 and an intercept of 0.0. The coefficient of determination (R^2), a measure of the variance in the simulated data that is attributable to the variance in the observed data, was calculated for each linear regression.

The coefficient of efficiency (E) is a calibration statistic used by hydrologists to represent the deviation of the simulated versus observed regression line from the 1:1 line. The modified coefficient of efficiency recommended by Legates and McCabe (1999) was used:

$$E = 1.0 - \frac{\sum_{i=1}^{N} |O_i - P_i|}{\sum_{i=1}^{N} |O_i - \overline{O}|} \qquad (1)$$

where O represents observed values, $\overline{O}$ is the mean of observed values, and P represents predicted values. This form of the coefficient of efficiency is considered more conservative than the statistic developed by Nash and Sutcliffe (1970) that uses squared error terms. The coefficient of efficiency varies from minus infinity to 1.0, with a value above 0.7 generally considered a good fit (Legates and McCabe, 1999).

Calibration Scenarios

Comparison of the observed flows during the pretreatment period indicated that outflow from catchment D2 was greater than from D1 on a per unit area basis (Chescheir et al., 2004). Much of this difference was attributed to the continuous baseflow that occurred at D2 and not at D1 (fig. 5). Two hypotheses have been put forth to explain these differences in observed flows. One hypothesis theorizes that evapotranspiration on a per unit area basis is less from catchment D2 than from catchment D1 due to differences in soil properties of the sites. The other hypothesis theorizes that groundwater flows into the D2 catchment from areas outside of the catchment boundary. Two modeling scenarios were therefore developed as potential explanations for the observed discrepancy in baseflows between catchment D1 and D2. These scenarios are referred to as the reduced evapotranspiration scenario (reduced ET) and added groundwater scenario (added GW). The model was calibrated and validated for these two scenarios.

Under the reduced ET scenario, the primary source of baseflow to the catchments was from the higher elevation soils in the upper plateau and cliff areas (soils A and B), as well as along the catchment divide (soil E). Due to the shallow depth of these soils, the soil rooting depth and water storage capacity were assumed to be small, while the infiltration and percolation rate were assumed to be large. As a result of these assumptions, the model simulated lower evapotranspiration from the areas with A, B, and E soils (evapotranspiration approximately 50% of the other soils). Since the treatment catchment (D2) has the greater extent of A, B, and E soils, the simulated baseflows were greater in catchment D2.

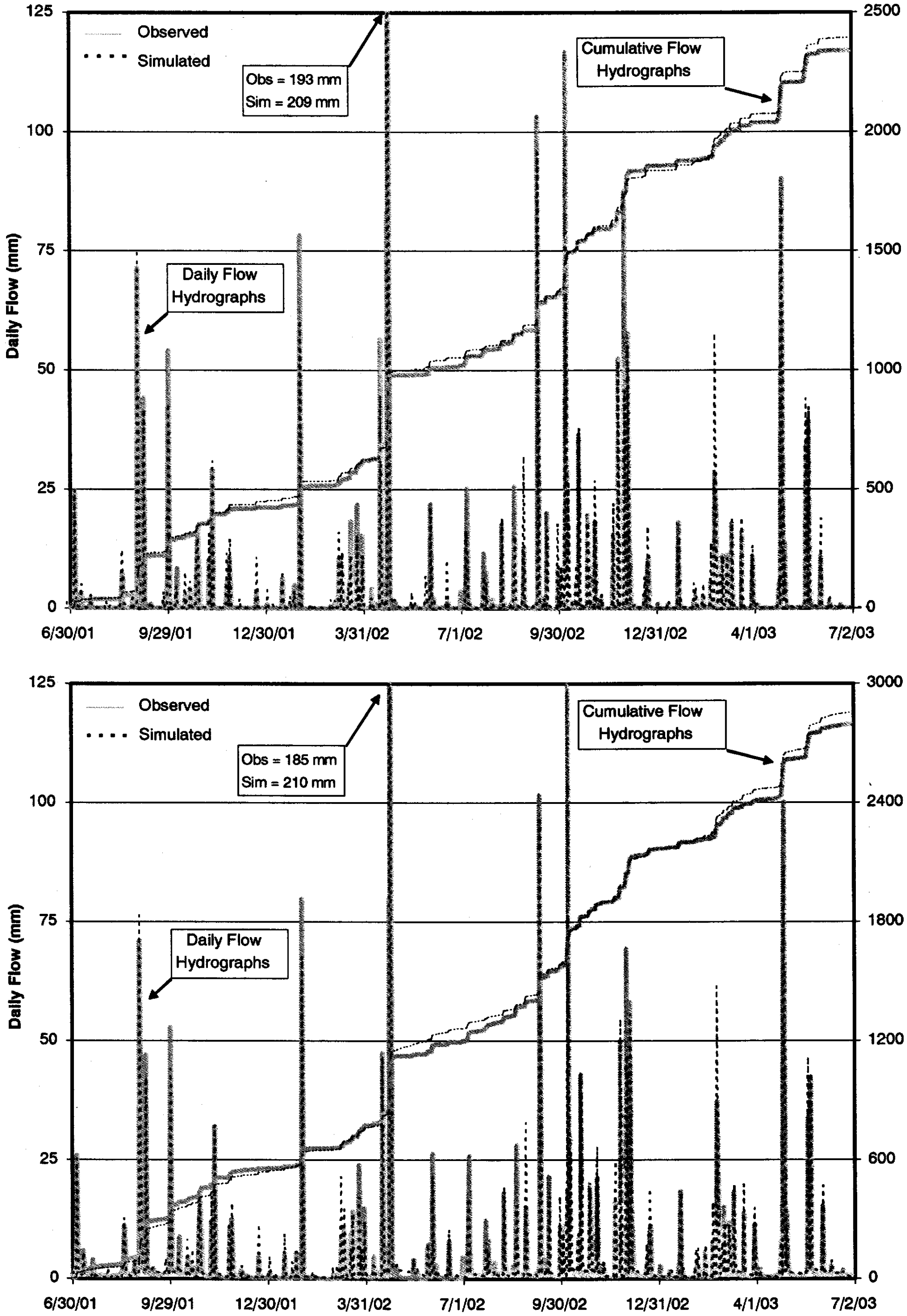

Figure 6. Simulated and observed daily flow and cumulative flow hydrographs for catchments D1 (top) and D2 (bottom) for the reduced ET scenario during one calibration year (2001-2002) and one validation year (2002-2003).

For both calibration scenarios and both catchments, the annual water yields were underpredicted by the model in 2000-2001 (1 July to 30 June, typical) and overpredicted in 2001-2002, although the errors were generally small (table 4). In 2001-2002, most of the error was due to a very large multi-day storm (22-24 April 2002). The accuracy of the observed flow measurements for this storm was questionable, as both outlet flumes were overtopped, requiring flow stages and rates to be estimated (Amatya et al., 2002). The rain gauges also showed inconsistent rainfall amounts during this time period. Hence, simulated and observed water yields (table 4) are shown including and excluding the 22-24 April storm for 2001-2002.

Annual water yields simulated by the SWAT models were within 2.5% of the measured values during the first validation year (2002-2003) for both scenarios and both catchments. The models overpredicted water yield for catchment D1 and underpredicted water yield for catchment D2. The catch–

Two different hydrologic scenarios for the pretreatment catchment condition (reduced ET and added GW) were successfully calibrated and validated using the SWAT model on a daily time step. These two scenarios were intended to simulate the discrepancy in observed baseflows between catchments D1 and D2. The two modeling scenarios had similar total and storm flow predictions, as well as baseflow predictions for catchment D1, during the pretreatment period. The reduced ET scenario appeared to predict baseflows in catchment D2 slightly better than the added GW scenario; however, the mean absolute difference between the scenarios was smaller than the mean absolute error between the predicted and observed baseflows. Although the model simulations are inconclusive as to which scenario provides a better explanation of the hydrologic processes occurring on the research catchments, they do provide insight as to which watershed characteristics warrant further investigation. One such characteristic to investigate during the continuing field study will be the growth of trees in the shallow soils where ET was theoretically reduced in the reduced ET scenario. If ET is actually reduced, then future growth measurements such as leaf area index and biomass will be lower for trees growing in these shallow soils than for those growing on the deeper soils.

The calibrated models of both scenarios overpredicted outflow volumes from catchment D1 during the dry year (table 3). The overprediction of storm flows was primarily attributable to the model assigning too high a curve number during dry conditions (antecedent moisture condition I). The overprediction of baseflows indicates an underrepresentation of evapotranspiration and/or soil moisture storage. Further information regarding watershed characteristics would be needed in order to conclude what process was being misrepresented in the model. The flow during years with above-average rainfall was better predicted. The consequence of overpredicting outflows during and following dry periods on the model's ability to predict the effect of afforestation was anticipated to be small. However, the effect of the pine plantations on water yield is of greater concern during drought conditions, when water supply is low and baseflows are diminished. Due to the concerns regarding the performance of the model during dry periods, the evaluation of the predicted hydrologic effect was limited to long-term mean annual water yield rather than focusing on the impacts during years with below-average rainfall.

Based on the analysis of the results, the calibration and validation of the models were considered good and appropriate for evaluating the difference in the hydrologic response of the two catchments and for predicting the hydrologic effects of pine afforestation.

Model Application Scenarios

Only the reduced ET calibrated model was used for the model application scenarios, since the results of the reduced ET and added GW models were similar for the calibration and validation simulations.

Land Use Treatment Scenarios

The mean annual components of the water balance were calculated for the various land use treatment scenarios for catchment D2 for the period 1971 through 2003 (fig. 8). The water yield in SWAT is divided into three flow pathways: overland surface runoff, lateral shallow subsurface flow (sometimes referred to as interflow), and groundwater flow from the shallow aquifer. Water is lost from the system through evapotranspiration and percolation to the deep aquifer. The grassland cover without grazing had 15% less mean annual water yield than the grassland with livestock grazing. This was primarily due to the fact that the grassland without grazing had lower curve numbers, resulting in less surface runoff than grassland without grazing. In addition, the grassland without grazing had greater loss resulting from evapotranspiration due to greater leaf area of the grass coverage. For the grassland with grazing, the livestock continuously consumed vegetation, thereby preventing the grass from reaching maturity and resulting in reduced evapotranspiration through the growing season and more runoff.

The pine tree cover had less water yield than the grassland without grazing cover due to the deeper roots and the greater leaf area of the trees during the growing season. The deeper roots of the trees allow greater access to the water in the soil,

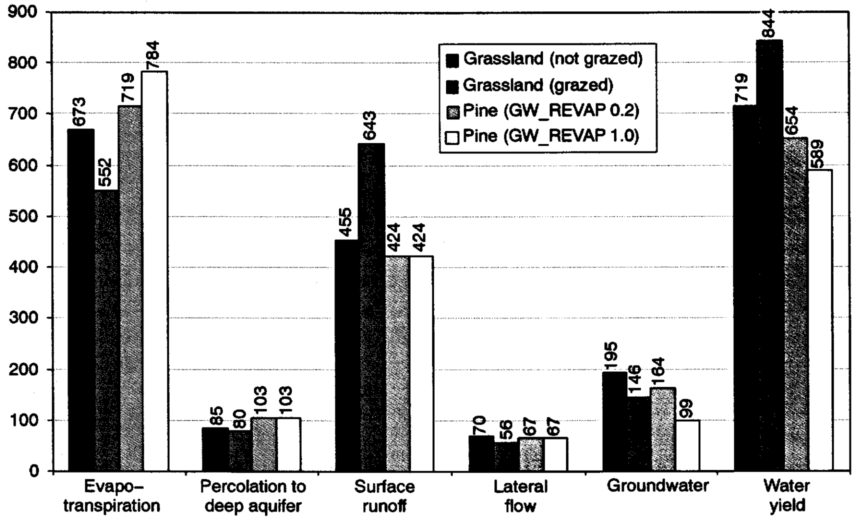

Figure 8. Mean annual water yield and water balance components from catchment D2 for land use treatment and root depth penetration scenarios. (Mean annual precipitation was 1477 mm, and mean annual potential evapotranspiration was 1131 mm).

Table 6. Mean daily baseflow for grassland with grazing land use and effect of pine treatment root penetration for catchment D2.

	Mean Daily Baseflow (mm)		
Season	Grassland with Grazing	Treatment (GW_REVAP 0.2)	Treatment (GW_REVAP 1.0)
Annual	0.47	0.53	0.35
Summer	0.33	0.46	0.29
Autumn	0.62	0.62	0.42
Winter	0.52	0.67	0.44
Spring	0.35	0.32	0.22

the treatment vegetation and the relative lack of access of the pine trees to the groundwater. The pine treatment with GW_REVAP of 1.0 resulted in a reduction in mean daily baseflows of 24% (table 6) due to the greater access of the pine trees to the groundwater. There was a large seasonal variation effect on mean daily baseflows, with the greatest reductions occurring during the summer season (22 December to 21 March). The summer season had the lowest baseflows, primarily due to a lower water surplus (precipitation minus PET).

Selection of the groundwater revap parameter is significant due to its effect on baseflows. The value of 1.0 for the groundwater revap fraction represents the greatest reduction in water yield resulting from the afforestation of catchment D2 (fig. 8). The actual value of the groundwater revap fraction is likely somewhere between 0.2 and 1.0. Further monitoring of the catchments as the pine trees mature and further refinement of the model for the treatment condition will be required to select the appropriate value for the groundwater revap parameter.

Conclusions

Based on the modeling results, pine afforestation of catchment D2 was predicted to reduce mean annual water yield from the landscape by 23% as compared to the grassland with grazing pretreatment condition. The difference in flow volumes was predicted to occur primarily during the less frequent storm flows, with a minor increase in baseflows predicted (14%). Therefore, at the treatment rate of catchment D2 (approx. 60% pine and 40% grass), the afforestation was not predicted to have detrimental effect on baseflows. The level of effect observed in the field will depend on the pathway of subsurface flow and the access of the tree roots to water in the ground.

Simulation of grassland without livestock grazing resulted in decreased water yield as compared to the pretreatment condition of grassland with grazing. This difference was primarily due to the lower curve numbers associated with undisturbed grass as compared to grazed grass. The lower curve numbers for the ungrazed grass resulted in less runoff, more infiltration, and greater evapotranspiration. Previous studies have shown that infiltration is reduced (Gifford and Hawkins, 1978; Branson et al., 1981) and runoff is increased when grasses are subjected to grazing (Holechek et al., 2004). Further investigation is recommended to determine if the increase in water yield due to grazing predicted by the model is observed. The removal of livestock is an important consideration when quantifying the hydrologic effects of afforestation, as the pine treatment of catchment D2 has nearly 40% grassland cover in protected riparian areas and between planting zones.

An important consideration in the evaluation of the hydrologic effects of afforestation is the ability of deep-rooted trees to remove groundwater from lower portions of the soil profile and shallow aquifer. The soil profiles of the map units on the catchments were typically shallow, ranging from 10 to 175 cm. The calibrated model had a maximum rooting depth of 1.5 m for the grass vegetation, which is consistent with the literature and resulted in good prediction of outflows from the catchments during the model calibration period. The grass vegetation had access to water throughout the soil profile due to the shallow soils, thereby reducing the effect of introducing deeper-rooted trees. There is the potential for the tree roots to extract water from the rocky parent material underlying the soils. The groundwater revap (GW_REVAP) parameter for the pine trees was set to its maximum of 1.0 to simulate this phenomenon. Incorporating the maximum groundwater revap parameter, the mean annual water yield was reduced by 30% due to the conversion from grassland with grazing to pine trees. The additional reduction in water yield was entirely from the more frequent baseflows, which were reduced by 24%.

The actual effect on water yield of the afforestation is likely to fall somewhere within the range predicted by the various land use treatment and root penetration scenarios simulated in this study (23% to 30% reduction). This prediction could be improved through increased understanding of the subsurface hydrologic processes and groundwater conditions in the catchments.

Acknowledgements

The authors gratefully acknowledge the assistance provided by the staff of Colonvade, S.A., in gathering data used for this study and in providing logistical support for fieldwork. We also thank David B. Beasley, William F. Hunt, Garry L. Grabow, Jane Frankenberger, and two anonymous reviewers for providing suggestions and criticism to earlier drafts of the manuscript. The work is a product of the North Carolina Agricultural Research Service, North Carolina State University (Raleigh, N.C.). Funding was provided by the Weyerhaeuser Foundation, Instituto Nacional de Investigación Agropecuaria (INIA), and Colonvade, S.A.

References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: United Nations FAO.

Amatya, D. M., G. M. Chescheir, and R. W. Skaggs. 2001. Effects of afforestation on the hydrologic behavior of a basin in the Tacuarembó River. Progress report for 2000-01 submitted to Weyerhaeuser Foundation. Raleigh, N.C.: North Carolina State University, Department of Biological and Agricultural Engineering.

Amatya, D. M., G. M. Chescheir, and R. W. Skaggs. 2002. Effects of afforestation on the hydrologic behavior of a basin in the Tacuarembó River. Progress report for 2001-02 submitted to Weyerhaeuser Foundation. Raleigh, N.C.: North Carolina State University, Department of Biological and Agricultural Engineering.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I.